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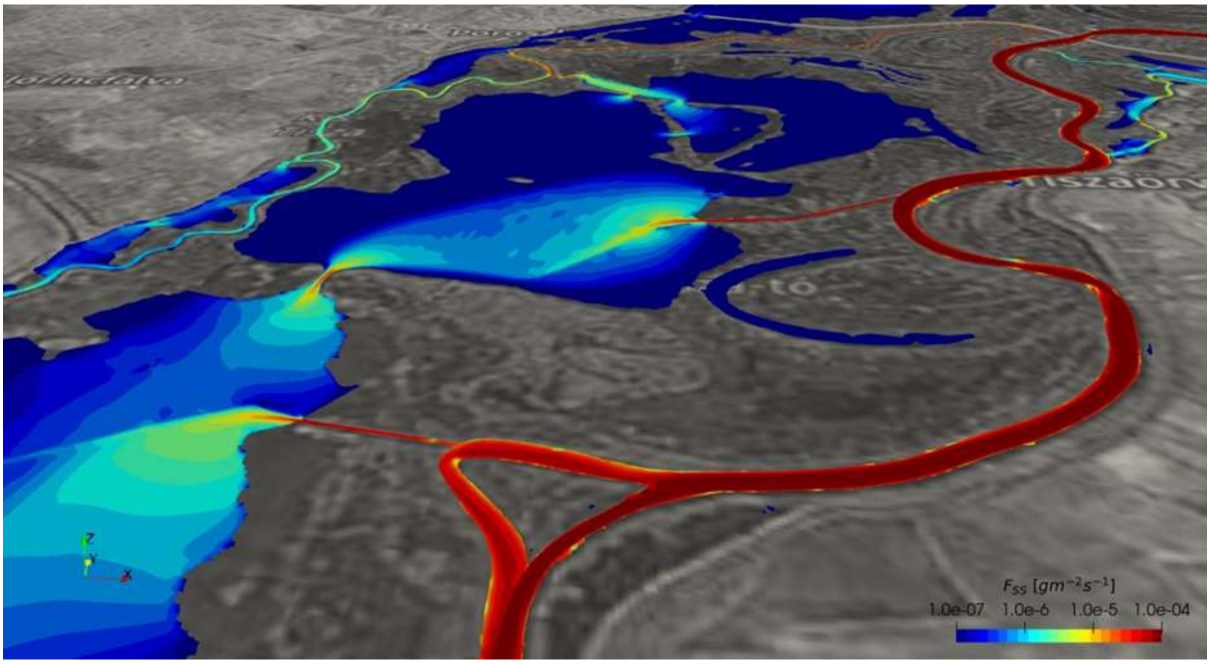
Case study supporting the operation of the hydropower plant from sediment quality point of view



SIMONA

Lake Tisza: Three-dimensional numerical modeling-based analysis of reservoir flushing

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Introduction

Reservoir sedimentation

When water enters a reservoir, flow velocities, turbulence and bed shear stress decrease dramatically, which facilitates the settling and deposition of fine sediment particles. Long-term sedimentation entails a range of technical and management related issues in reservoirs and hydropower plants (HPP). Mahmood (1987) estimates that 1% of the capacity of the world's hydropower reservoirs is lost annually because of sedimentation, highlighting that the problem is a worldwide occurring one. However, the rate of sedimentation is not uniform distributed and strongly depends on the hydrology and the land use in the watersheds.

One of the most common and obvious problem related to sedimentation comes from the subsequent loss of potential water storage over time. Storage loss may lead to limited recreational and industrial (e.g., irrigation) use of these water bodies, while reduced hydropower capacities are often considered to be the most relevant, due to the economic consequences.

HPPs are affected in three major ways by reservoir sedimentation (Haun & Olsen, 2012): through the loss of storage capacity, which in extreme cases can mean that the reservoir is fully filled up; ii) increased flood risk by the reduction of retention volume; and iii) sediments entering the power intakes may abrade the turbines and/or completely block the way of the water.

Reservoir flushing

Reservoir flushing is widely practiced in many parts of the world to resolve – some of the abovementioned – issues related to sedimentation. The basic principle behind this kind of operation is opening the bottom outlets of the dams – usually leading to the erosion of deposited materials. During flushing the water level is drawn down which results in increased velocities, turbulence, bed shear stress and thus facilitates sediment transport.

While the main purpose of reservoir flushing is to improve the overall state and quality of the reservoir, as well as to increase potential hydropower capacity, it is also noted that in the short run, it results in the loss of a huge amount of stored water, which may lead to serious economic consequences. In addition to the financial implications, reservoir flushing often have dramatic ecological outcomes as well, both on the reservoir, as well as on the downstream side.

The effectiveness of reservoir flushing is a function of a number of hydrological, hydromorphological and sedimentological parameters, such as discharge, pace of the drawdown, reservoir morphology or sediment characteristics. An example of a successful application of reservoir flushing is the Mangahao reservoir in New Zealand, where 59% of the original storage volume was lost after 45 years of operation. With the first flushing, 75% of the deposited sediments were removed within 1 month (Jowett, 1984).

Numerical modeling of flushing

Due to the serious economic and ecological implications, there is a legitimate demand for predicting the process and outcome of reservoir flushing. There are two major means for this in the hydraulic engineering practice: physical and computational fluid dynamic (CFD) modeling. In case of the former, the whole system is scaled down to laboratory scale. Such experiments are rather time consuming and expensive, not to mention that there are notable uncertainties in the scaling of sedimentological information. Numerical modeling on the other hand can offer solutions in prototype scale faster and cheaper. A huge advantage of CFD over physical modeling is the fact that it is very simple and easy to analyze a range of scenarios even simultaneously, when the necessary computational capacities are available. The evaluation and comparison of numerical model results is also a lot easier, as the spatial distribution of all of the relevant hydrodynamic and morphological parameters are inherently available during the simulations, whereas in case of laboratory experiments, one must continuously monitor the different variables (usually with a range of instruments).

Nowadays, CFD modeling is considered a modern method for the prediction of reservoir flushing processes, and hence a tool for the planning and optimization of flushing. In most of the cases, up-to-date three-dimensional (3D) modeling tools are required with proper free surface treatment, due to the presence – and prominent role – of secondary currents.

Haun & Olsen (2012b) used the widely recognized 3D CFD tool SSIIM (Sediment Simulation In Intakes with Multiblock option) for the morphodynamic simulation of reservoir flushing in laboratory scale. The physical model experiment used for model verification was constructed to mimic the conditions in the Kali Gandaki hydropower reservoir (Nepal). The numerical model reproduced the measured bed changes fairly well, making the study one of the first successful attempts to numerically predict the morphological impacts of reservoir flushing.

Haun & Olsen (2012a) also published the first attempt for the 3D modeling of reservoir flushing in prototype scale, using the same CFD code. In order to build and parametrize the model, field measurements were performed to obtain bathymetry and grain size distribution information. It is noted, that in contrast with most physical model experiments, the grain size distribution in real life conditions usually have a nonuniform nature, which was also taken into account in the CFD modeling. The model provided reasonable results in prototype scale as well, however, differences were naturally observed as a result of the numerical approximation methods and the adopted simplifications in general. The authors note some of the potential ways to improve the numerical model in order to provide better predictions of erosion shape and location, such as implementing algorithms for bed form modeling, solid mechanic issues, cohesive sediments and sand slides. The study underlined the relevance of 3D modeling in reservoir modeling, as velocity profiles are usually not logarithmic, hence the vertically resolved profiles offer better suspended sediment transport and bed shear stress estimation as well.

Another successful numerical modeling case study is reported by Haun et al. (2013), where the suspended sediment transport as well as morphological changes in the Angostura reservoir (Costa Rica) were predicted for an entire operation year. The numerical model was validated with detailed field measurements of suspended sediment concentration (SSC) verticals. The authors emphasized the role of higher-order discretization schemes in the accurate capturing of suspended sediment transport and SSC profiles in particular. Although the model performed reasonably well, lower accuracy was observed where complex flow conditions and/or high sediment concentrations were present. Total sediment deposition was calculated with a 10% deviation; however, the general deposition pattern was predicted with reasonable overall quality.

Esmaeili et al. (2017) successfully employed SSIIM for the modeling of the Dashidaira reservoir (Japan) in prototype scale. Their results highlighted the importance of the proper choice of bed load transport model (Meyer-Peter-Müller vs. van Rijn) for sediment flushing simulations and underlined the inherent limitation of these widely used empirical formulas as well.

The abovementioned studies demonstrated the applicability of SSIIM for the numerical modeling of reservoirs, even in prototype scale.

Sediment quality aspects

Soil erosion is one of the top sources of sediments in rivers, and as such, its quality and contamination mainly determines river sediment quality. As a significant amount of global sediment flux is retained in reservoirs, the quality of accumulating sediments is of major importance. Contaminated sediments can have significant environmental consequences in reservoirs. Water quality may be affected due to nutrients and oxygen deficiency. Serios hazards may occur if the bottom sediment is contaminated with heavy metals and other harmful chemical substances. Oxygen deficiency is usually a consequence of chemical and bacterial reactions that consume oxygen. There is a serious risk that the contaminated sediments could be released into the water body during reservoir flushing or similar operations (Dargahi, 2012). Although these issues are out of the scope of this study, the authors note that the quality aspects of reservoir sediments can also be assessed via numerical modeling tools (see e.g., Heidarzadeh & Motiey Nejad, 2018).

Lake Tisza

In this chapter, a general overview will be given on Lake Tisza (Figure 1), its structure and seasonal operation, as well as on the Kisköre Dam (responsible for controlling the water levels in the reservoir). The following overview is translated from the Hungarian description from the webpage of the General Directorate of Water Management[1].

History

Lake Tisza is the third largest, yet youngest lake of Hungary. Its original name is Kisköre Reservoir, as the increased water levels are granted by the Kisköre Dam. On its easter boundary, it is bordered by the Tisza river; its marked contour is provided by the flood protection dike system. Prior to the regulation of the Tisza River (until the first half of 19th century), the area was a wild water territory. Initiated by count István Széchenyi, the regulation of the river started in the second half of the 19th century based on the plans of the best hydraulic engineer of the era, Pál Vásárhelyi. The constructions took more than a century to finish. Lake Tisza is an artificial reservoir laying in the floodplain of the Tisza River – bounded by the aforementioned dike systems. Since 1978, the reservoir is considered a special natural treasure as nature has been continuously reclaiming the area and formed a landscape similar to the pre-regulation times. This entailed the return of a flourishing flora and fauna as well.

[1] https://www.vizugy.hu/index.php?module=content&programelemid=45

Figure 1 Orthophoto of Lake Tisza.

General description

The current water coverage is a result of the second damming phase (1978) of the Kisköre Dam. The Kisköre Reservoir (geographically Lake Tisza) is wonderful creation of nature and the humankind. The unparallelly diverse ecosystem developed continuously, resulting in a natural richness similar to historical times, prior to the regulation of the Tisza River. Nowadays, the lake can be characterized with large open water surfaces, a complex network of channels, islands, peninsulas and intense and diverse vegetation (reeds, etc.).

The lake is located on the upstream side of the Kisköre Dam between river kilometers (rkm) 404–440 (Kisköre – Tiszabábolna). The length of the lake along its midline is 33 km, its largest width is 6.6 km while the narrowest area (Tiszaderzs) its width is 0.6 km. The total length of the bounding flood protection dikes is 80 km. The total surface area of the reservoir is 127 km^2, from which 104 km^2 is the water surface (62 km^2 open water; 42 km^2 vegetated), while the area of islands and peninsulas is approximately 23 km^2. The depths of the different basins are varying. In case of the huge – once plain (meadow, pasture, etc.) – areas, water depths vary between 0.8–2.0 m. Natural watercourses and artificial flushing channels have depths of 2.0–5.0 m. The deepest areas are in the main channel of the river, reaching up to 10–20 m. The average water depths in each basin are as follows:

- Gulf of Abádszalók: 2.5 m,
- Sarudi basin: 1.5 m,
- Poroszlói basin: 1.3 m,
- Tiszavalki basin: 0.7 m.

The total water volume of the reservoir is 253 million m^3, from which 132 million m^3 is utilizable. The most important facilities of the water distribution system are the Jászsági Irrigation Main Channel (capacity of 48 m^3/s) and the Nagykunsági Irrigation Main Channel (capacity of 80 m^3/s), which are responsible for the satisfaction of irrigation water demands of the area. Additionally, the Nagykunság Irrigation Main Channel plays a crucial role in the mitigation of water shortage in the Körös-Valley and in ensuring ecological water replenishment. Lake Tisza is an artificial water body – a flow-through reservoir, and as such, its water level is a function of the all-time flow regime of the river. The Kisköre Dam can only keep water levels locally, the surface slope of the reservoir is a function of the river discharge. Being an artificial lake, the water level of the Lake Tisza can be controlled. The Tisza River flows through the reservoir in its own main channel. One of the most important characteristics of the lake is its mosaic nature, which provides complex and highly divers habitats.

Flushing channels and their role

Lake Tisza is a flow-through lowland reservoir. Due to its morphology, it is crucial to ensure proper water exchange between the basins and channels. Considering the artificial nature of the whole system, such an exchange system could not have been developed naturally – the processes have to be facilitated through engineering measures.

Water exchange and transport between the river and the basins take place in the flushing channels, as well as in natural watercourses. The construction of the 12 flushing channels started at the end of the 1970s. Their lengths vary between 1–4 km, while their width is in the range of 10–60 m. An exception is the 1st Flushing Channel, which has a width of 150 m at its confluence. At the Tisza-side of the estuaries nine water regulatory structures have been constructed starting in the 1980s, which can be either opened or closed. Their role is to ensure and control the water exchange and distribution, as well as to retain sediments and debris from the basins during floods. Such systematic control of the structures can help reducing the sedimentation of the basins and can protect them from possible contaminations as well.

Due to the clear importance of this water exchange system, the continuous maintenance and development of the channels is crucial for maintaining the quality and usability of the reservoir.

The faces of Lake Tisza

The lake shows five different "faces" during a year, from which four is controlled by men, while the fifth is independent from us. The nature of these periods is mainly determined by alteration of seasons, as well as by the dam operating protocol. The five hydrological periods are briefly introduced in the following subsections.

Winter period

The winter water level lasts nominally from the middle of November and lasts at least until the middle of February, but even up to the winter water level increasing. During the winter period, the water level can be one of the following two – depending on the conciliation of interests: either 560 ± 10 cm or 610 ± 10 cm, measured on the Kisköre-felső water level gauge. In case of increasing discharges, this is the level of equalization – the end of damming; in case of decreasing discharges – the beginning of damming.

Spring refilling period

The refilling period during the spring – transition from the winter period to the summer water levels – starts in the middle of February, or from the beginning of the winter water level increase until reaching 725 cm on the Kisköre-felső gauge but is finished no later than the middle of April. The ice conditions, the hydrological conditions, the water quality and the state of the reservoir should all be considered during the beginning of the water level increase. The maximal pace of the water level increase is 10 cm/day (measured on the Kisköre-felső gauge).

Summer period

The summer period starts after reaching the 725 cm level, but no later than the middle of April, and lasts at least until the middle of October, or until the beginning of the water level decrease from 725 cm. The summer water level has to be kept at 725 ± 5 cm, so that the state of the lake is stationary – providing a safety and predictability for the users. The summer period is the longest and is the best known by the utilizers and recreational users of the lake.

Autumn emptying

The period of the autumn emptying is the transition from the summer water levels to the winter period, which starts earliest in the middle of October or by the decrease of water level below the 725 cm level and lasts until reaching the winter water levels – nominally to the middle of October. The intensity of the water level decrease cannot exceed 10 cm/day.

Flood period

Flood waves can occur in every month of the year in the Tisza, with varying length and intensity. However, spring floods have the highest probability, nevertheless there are precedents for notable floods in every season. Flood waves first increase the water levels of the river, then – exceeding the elevation of the islands – reach the lake as well. The duration and the intensity of the flood wave determines the flood period – depending on the hydrometeorological conditions. There is no damming at the Kisköre Dam during floods, hence the arriving water fills up to lake up to 2-3 m above the well-known summer water levels. Islands get partially or fully inundated, the mosaic structure of the lake temporarily ceases, the morphologically complex reservoir turns into one huge basin of undisturbed water surface. After the flood waves, the lake returns to its seasonally actual state, however, major floods may leave a mark on the landscape.

Kisköre Dam

The Kisköre Dam is located in the border of Kisköre village, 403.2 km upstream from the Tisza estuary and was constructed between 1967 and 1973. The commissioning of the facility was on 16 May 1973. The facility consists of three major structures: i) the dam; ii) the hydropower plant and iii) the ship lock.

The segment gates at the five openings of the dam (24 m wide each) are responsible for controlling the water level up to a maximal water column of 11 m. Its main task is keeping the water level of the lake at the given values (according to the operating protocol) with a precision of 1 cm. Consequently, the lake could not exist without the Kisköre Dam. It also acts a flood risk mitigation tool of the Lower-Tisza area, as the reservoir can be utilized for flood wave attenuation purposes as well. The HPP is built next to the segment gates on the right bank, consisting of four tube turbines (diameter of 4.3 m each) built together with generators. The maximal flow rate through the turbines is 4×140=560 m^3/s. The total output performance of the generators is 28 MW; the annual produced energy is between 80 and 110 million kWh. The turbines can operate between head losses of 2.0–10.7 m. The ship lock is located on the left bank. Its usable size is 85×12 m, which fulfils the standards of a IV. class international waterway. The ship lock can used to sluice ships and barges up to a total mass of 1350 tons. A fish pass is located on the right-side wall of the ship lock – operating during fish migration.

Numerical modeling case study of Lake Tisza

In this chapter a case study will be presented for the 3D morphodynamic modeling of Lake Tisza. The whole process will be presented starting with the model building and finishing with the post processing of the numerical results.

Objectives

The main goal of this study is to present the feasibility of the 3D CFD modeling of a complex hydromorphological system on the example of Lake Tisza, through the followings:

- Showing that the model is capable of reproducing the driving hydrodynamic characteristics of the reservoir.
- Presenting that the hydrodynamic solution can be coupled with suspended sediment transport, and thus the spatiotemporal behavior and the fate of the suspended sediments can be predicted through the presented numerical modeling-based approach.
- Underlining the relevance of 3D CFD modeling in optimized reservoir operation from the aspect of sediment management through the numerical simulation of different hydrological and operating scenarios.

Input data

The following data was provided/available to support the computational modeling experiments:

1. the digital elevation model (DEM) of Lake Tisza;
2. the orthophoto of the reservoir area (relevant for distinguishing open-water and reeds);
3. operating rules and protocols of the Kisköre Dam and basic hydrological information regarding the river and the lake.

The list above follows the logical order of numerical modeling as well – the base of the model (i.e., the computational gird) is built using the DEM, which is then parametrized with varying roughness values for the adequate numerical differentiation of varying surfaces (e.g., riverbed, reeds). Then the parametrized model can be used to perform numerical experiments for given hydrological and operating scenarios.

Digital elevation model

The digital elevation model (DEM) of the reservoir was provided in raster format, with a uniform horizontal resolution of 5 m. The DEM covers the whole area of interest (the morphology of the reservoir, the Tisza River and all of the major water courses of the water distribution system, as well as the flood protection dikes) represented in a sufficiently high spatial resolution (**Figure 2**).

Figure 2 Digital elevation model of Lake Tisza.

Applied numerical model

The three-dimensional (3D) numerical model SSIIM (Sediment Simulation In Intakes with Multiblock option) was used in the study for the morphodynamic analysis of Lake Tisza. SSIIM is developed at the Norwegian University of Science and Technology (NTNU) and was one of the first CFD models offering such three-dimensional morphodynamic simulations. The model is under continuous development and has been used for the numerical analysis of reservoir sedimentation for a decade now (see *Numerical modeling of flushing*).

The CFD model used for the morphodynamic analysis of Lake Tisza describes the study domain with a structured, curvilinear grid system horizontally, whereas a flow depth dependent number of layers is used vertically. The model solves the 3D Reynolds-averaged Navier–Stokes (RANS) equations, providing local information about the hydrodynamic pressure and the three flow velocity components throughout the entire computational domain. The turbulent nature of the flow is simulated via the so-called *k-ε* turbulence model, which enables the modeling of sediment transport capacity, as well as the bed shear stress field – both playing a crucial role in the morphodynamic behavior of water bodies, and reservoirs in particular. The detailed description of the numerical model can be found in the manual of Olsen (2018).

The model of Lake Tisza

Computational grid

The 3D model was built between the 404–440 rkm of the Tisza River, which covers the whole area of the reservoir as well. The computational domain is horizontally represented with a structured curvilinear mesh consisting of tetragon elements only. The domain consisted of 2765 × 566 elements, resulting in a total number of ~1.56 million cells. The average size of the computational cells was 15 × 15 m, however, the spatial variability was notable, as the computational mesh was fitted to the dominating curvature of the domain (**Figure 3**). The vertical cell allocation was changing adaptively during the simulations as a function of local water depths.

Figure 3 Section of the computational grid with an orthophoto as background.

The given DTM raster was used to interpolate surface elevations to each node of the computational mesh, which resulted in the final computation domain presented in Figure 4. It is noted, that the DTM and the computational domain has been partially extended, in order to make the proper structured representation of the reservoir possible. Additional (flood protected, hence dry) areas were logically incorporated in the computational domain, however, due to the high elevations, these areas did not affect the numerical simulations in any way (see these areas in red in Figure 4).

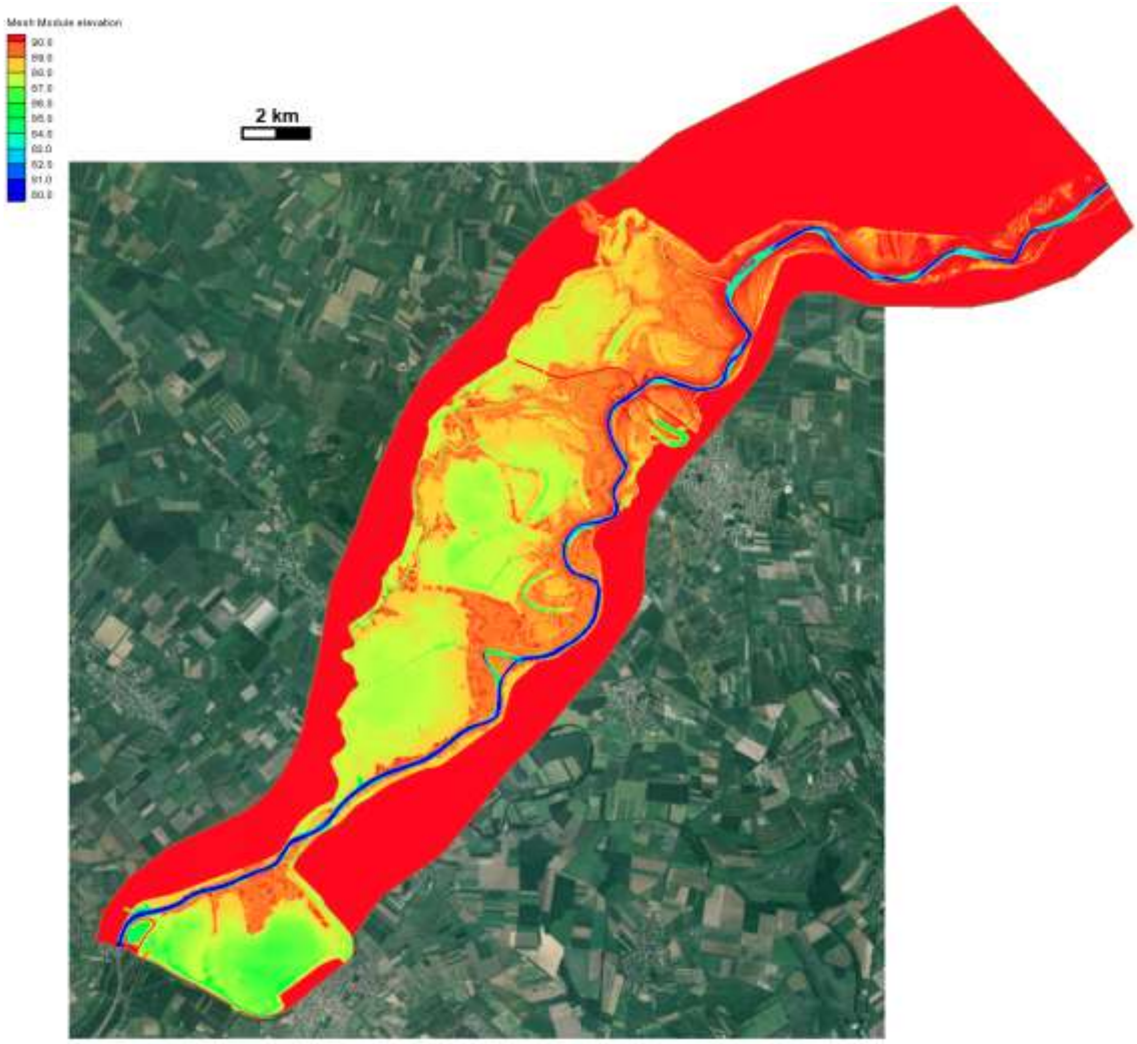

Figure 4 The total computational domain colored by elevation.

Modeled scenarios

Six schematic hydrological/operation model scenarios have been defined for the numerical simulations. All simulations were started from a state close to mean water flow conditions (Q_{Tisza} = 200 m^3/s; $h_{Kisköre}$ = 88.0 m a.s.l.) for which the hydrodynamic solution was calculated in advance. Five numerical simulations aimed to investigate the effect of five different types of dam operations on suspended sediment transport during a flood wave. The schematic flood waves started from the initial 200 m^3/s discharge and reached a max of 1000 m^3/s after a three-days-long linear rising limb. This discharge lasted for four days, then the discharge fell back to 200 m^3/s during a three-days-long falling limb (see in **Figure 5**). The suspended sediment concentration (c_{ss}) of the river follows the same scheme, with 20 g/m^3 during mean flow and 265 g/m^3 during the high-water condition. Moreover, an additional simulation was performed, where the initial condition (mean flow) was kept for 185 days, to see the influence of steady discharge and sediment yield in a larger timescale. The simulations aimed to mimic the following scenarios:

- **FW1** – Water is stored during the rising limb of the flood wave, then the water level is gradually decreased by 50 cm at the Kisköre Dam. The reduced water level is kept during the falling limb.
- **FW2** – No special dam operation is performed – the water level at the Kisköre Dam is steadily kept at the initial 88.0 m a.s.l.
- **FW3** – This scenario is the counterpart of *FW1* – the water level at Kisköre is increased by 50 cm after the rising limb during a 4-days-long period, then the increased water level is kept during the falling limb.
- **FW4** – In this scenario the drawdown of the water level starts at the very beginning of the flood wave, that is, before the flood wave reaches the Dam. Then, the water level at Kisköre is kept at the reduced level (87.5 m a.s.l.) until the end of the simulation.
- **FW5** – The flood wave is preceded by an additional 3-days-long period of mean water flow condition, during which water is collected in the reservoir before the drawdown – water level at Kisköre is increased by 50 cm. As soon as the river discharge starts rising, an intense drawdown (flushing) begins, upon which the water level at the Kisköre Dam is lowered by 1 m in three days. The water level is kept at this reduced state throughout the rest of the simulation.
- **MW1** – The initial mean flow condition is kept during a 185-day-long period. Discharge, sediment concentration and outflow water level are constant.

The transient boundary conditions (discharge of Tisza River, Q_{Tisza}; suspended sediment concentration of the Tisza River, $c_{ss,Tisza}$; water level at the the Kisköre Dam, $h_{Kisköre}$) for the abovementioned model scenarios are presented below in **Figure 5**.

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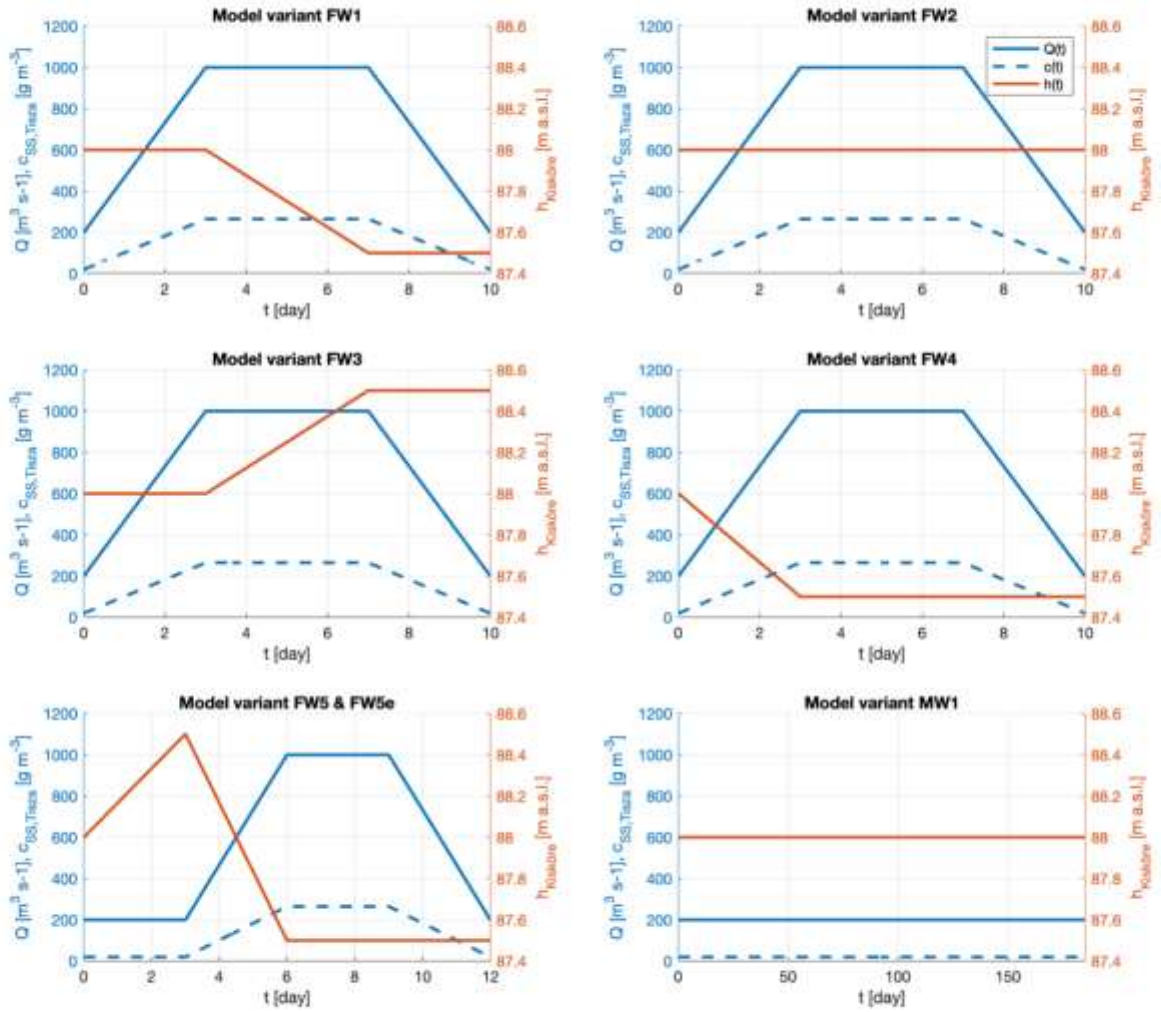

Figure 5 Transient boundary conditions for the numerical simulations. Each subplot represents a model scenario with the discharge, sediment concentration and outflow water level time series.

Results

In this chapter, results of the numerical modeling will be presented to highlight the hydro- and morphodynamic differences between the pre-defined scenarios. In order to give the reader an overview on the capabilities and main features of 3D CFD modeling, the first subsection will present some general examples of the results. The spatial distribution of the hydrodynamic and sedimentological variables can provide an easily understandable overview of the occurring phenomena, helping experts and decision makers as well.

Examples for numerical model evaluation

In this subsection an instantaneous timestep of the numerical simulation will be assessed to provide an overview on the main features of numerical morphodynamic modeling.

As a part of the hydrodynamic solution, the free surface elevation is calculated in every computational node. Keeping in mind, that the local bed elevation is also known throughout the whole computational domain (may also change over time), the horizontal distribution of water depths can be calculated (**Figure 6**). In addition to its hydrodynamic relevance, such information might be useful when the recreational or ecological (habitat) potential of the water body is to be evaluated.

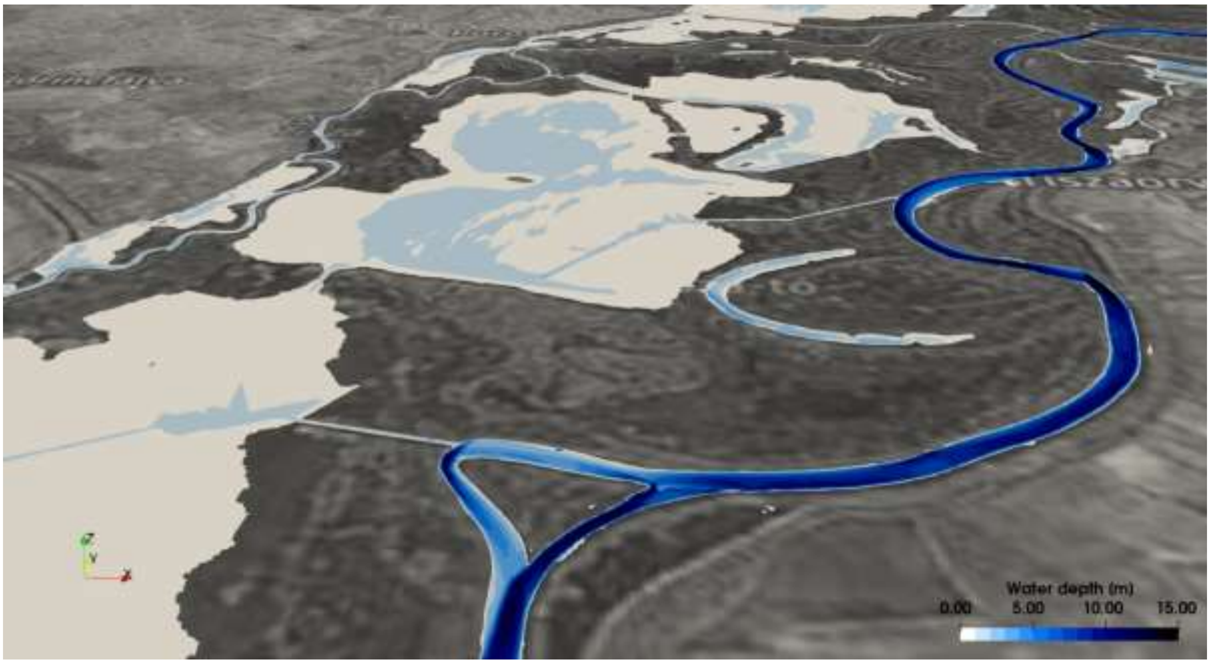

Figure 6 Example of the numerical model results for a section of the computational domain. The water surface is colored based on the local water depth.

The most relevant part of the hydrodynamic solution is the velocity field. The model offers not only the horizontal, but the vertical distribution of the 3D velocity vector field. In the following example (**Figure 7**) the surface velocities are presented for a section of the Tisza River and the Tisza Lake. The water surface is colored based on the surface velocity magnitude and velocity vectors are also presented to provide directional information as well. It is observed that in the presented case, velocities are much higher in the river, that in the shallower areas of the reservoir. The important role of flushing channels is highlighted – water exchange between the different parts of the reservoir and the river can be observed through the locally high velocities.

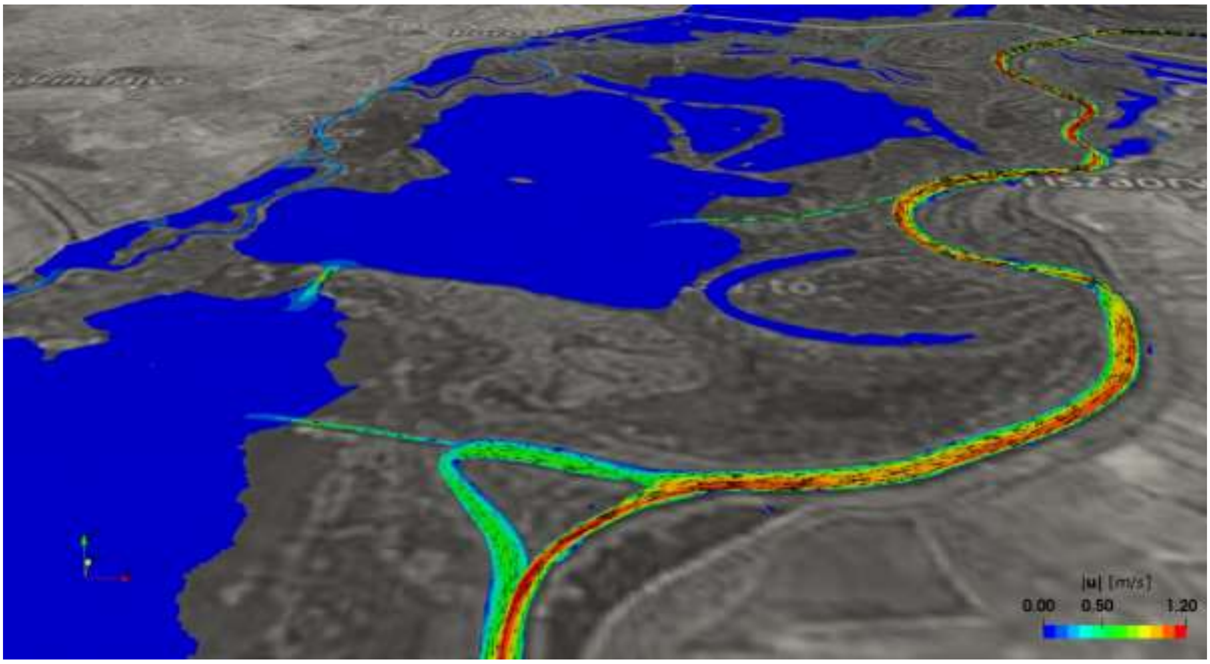

Figure 7 Example of the numerical model results for a section of the computational domain. The water surface is colored based on the local velocity magnitude in the near-surface layer.

The hydrodynamic model was coupled with a sediment transport module as well, which allow us to assess the quantitative transport of suspended sediments throughout the whole modeled system. In the presented simulation result (**Figure 8**), a flood wave is taking place which brings high suspended sediment concentrations in the river. Being the flushing channels opened, the arriving suspended matter can flow into the shallower areas of the reservoir, where – as a result of the low velocities and turbulence – its settling can be prognosed. This is the general process of reservoir sedimentation. The presented map shows the potential areas for sediment deposition, which may be crucial from the aspect of reservoir management.

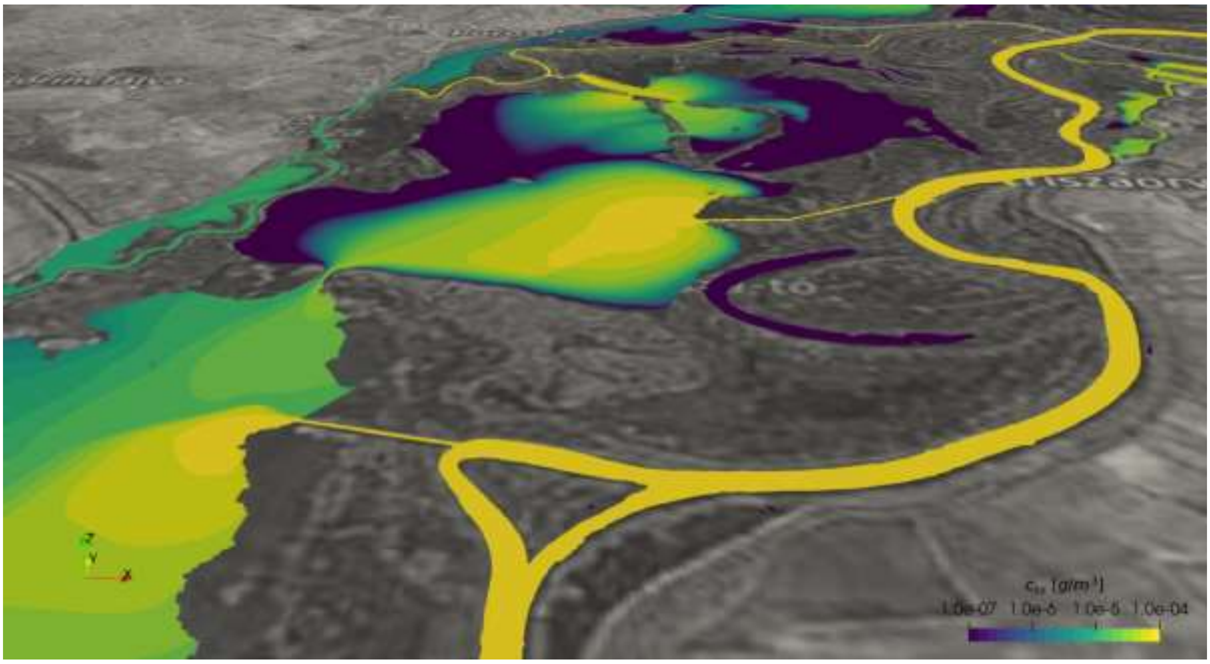

Figure 8 Example of the numerical model results for a section of the computational domain. The water surface is colored based on the local suspended sediment concentration in the near-surface layer. Note that the scale is logarithmic.

The combination of hydrodynamic and sediment variables can reveal underlying processes, which can help us understand the morphodynamic behavior of the reservoir. The suspended sediment flux vector ($\boldsymbol{F_{ss}}$) for example, can be derived at each computational cell using the 3D velocity vector ($\boldsymbol{u}$) and the suspended sediment concentration (c_{ss}). The spatial distribution of the rate of $\boldsymbol{F_{ss}}$ highlights the main routes of sediment transport, where most of the suspended matter is moving (**Figure 9**). The high velocities and concentrations in the river clearly make it the main transporter of the suspended matter, however, the dominant role of the flushing channels is again underlined from the sedimentological aspect as well. The results point out the importance of proper operation of the flushing channels in the prevention of reservoir sedimentation (see in 0).

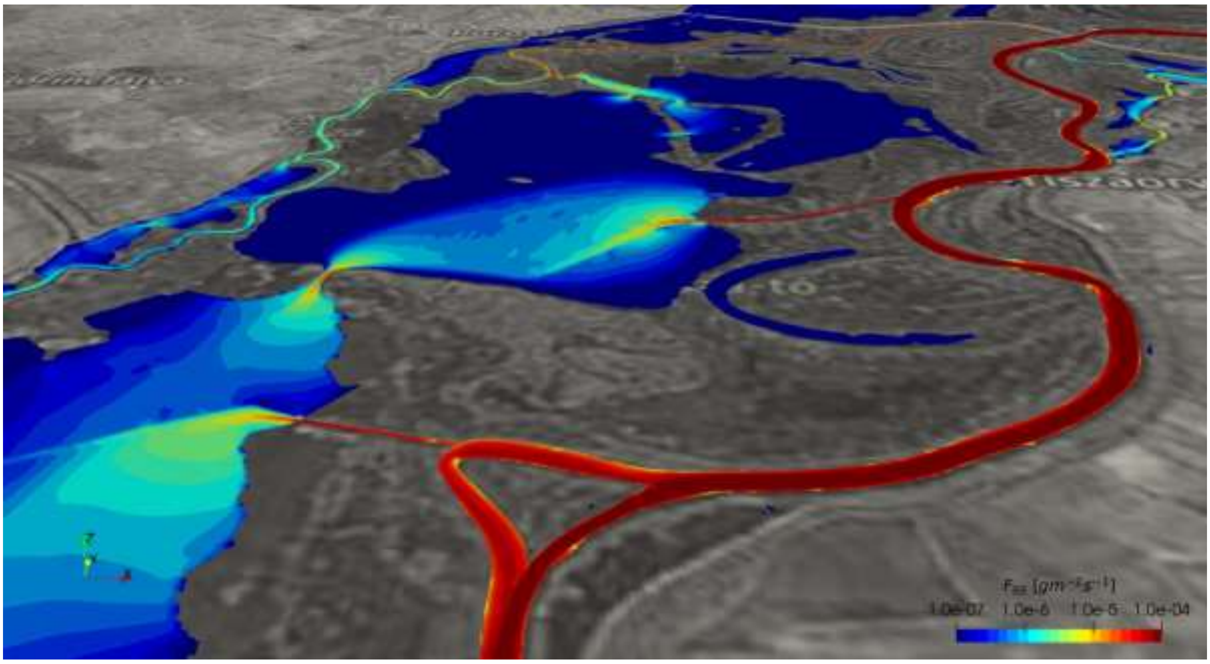

Figure 9 Example of the numerical model results for a section of the computational domain. The water surface is colored based on the local suspended sediment flux in the near-surface layer. Note that the scale is logarithmic.

The above presented examples give a glimpse on the most common result fields obtainable with numerical models, but it is noted that the hydrodynamic and sediment transport model offer an additional wide range of variables (e.g., turbulent kinetic energy, bed shear stress, deposition/erosion rate, etc.) which can be utilized for various aimed analyses.

Spatiotemporal complexity of the hydromorphological conditions

The spatiotemporal complexity of the hydro- and morphodynamic conditions during a simulated flood event is presented through the unsteady model results of the FW5 model variant. The total model simulation covers 12 days of real time – for each day an instantaneous model result is presented in the followings (**Figure 10** to **Figure 21**). Each result map consists of four subplots presenting i) the surface velocity distribution; ii) water depth distribution; iii) suspended sediment concentration and iv) the total bed elevation changes. The simulation starts with hydrological mean flow conditions in the Tisza river, then a rapid flood wave reach the domain brining large amount of suspended sediment. As the flood wave progresses downstream, the turbid water reaches the shallower parts of the reservoir through the opened flushing channels. The Kisköre Dam gets opened on day 3, aiming to reduce water levels, and hence increase flow velocities in the reservoir to prevent the settling of fine sediments. However, the operating protocol of the dam does not allow fast water level changes – the moderate flushing results in moderate effects in the reservoir. Fine sediments infiltrate the shallow areas of Lake Tisza and also settle by the end of the simulation. It is observed that sediment concentration gradually decreases in the basins, whereas the bed elevation increases as the result of the deposition. The maximal sediment deposition is around 1 mm during this relatively short flood wave, despite the attempt for flushing.

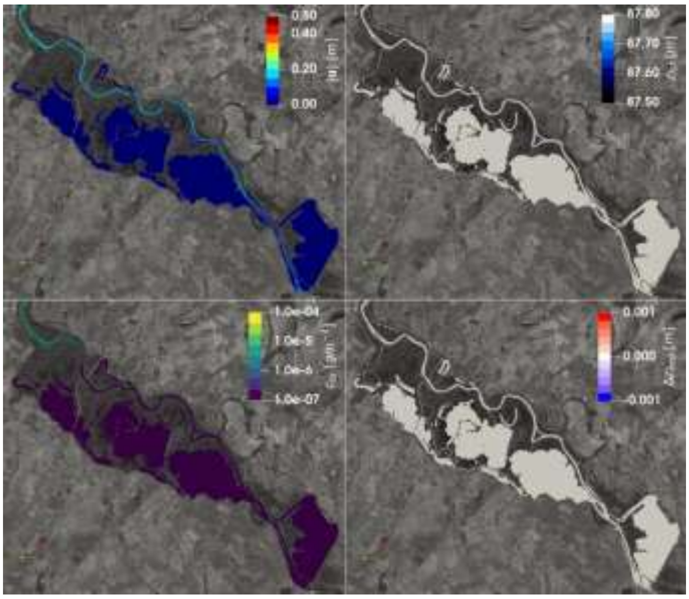

Figure 10 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 1.

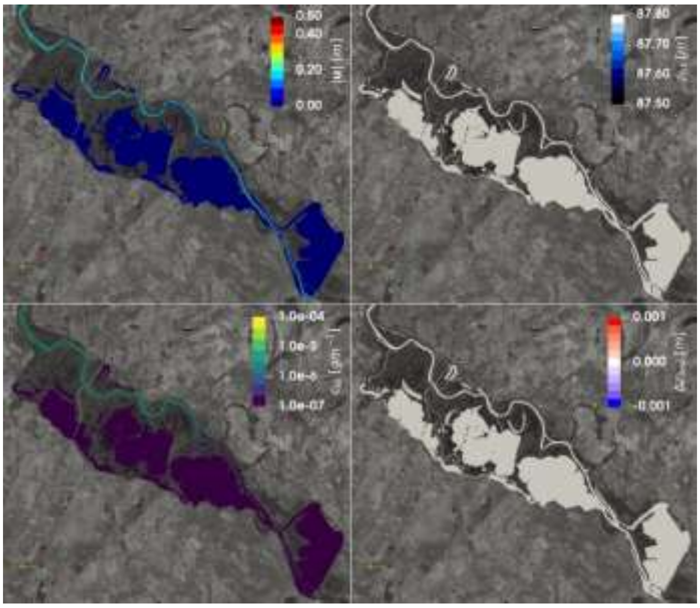

Figure 11 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 2.

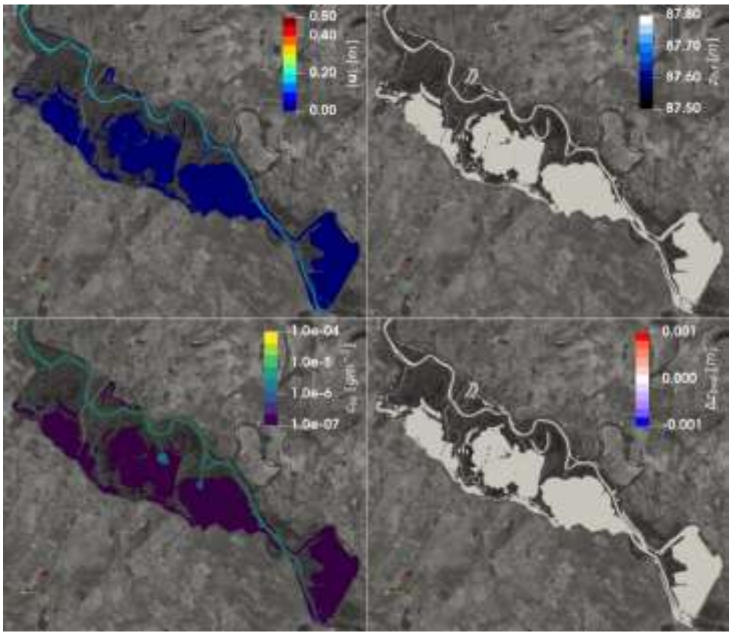

Figure 12 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 3.

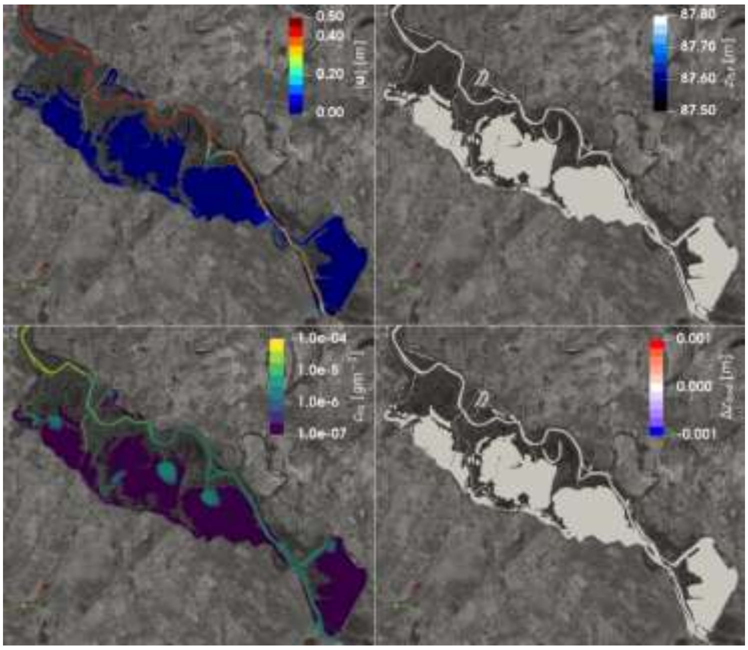

Figure 13 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 4.

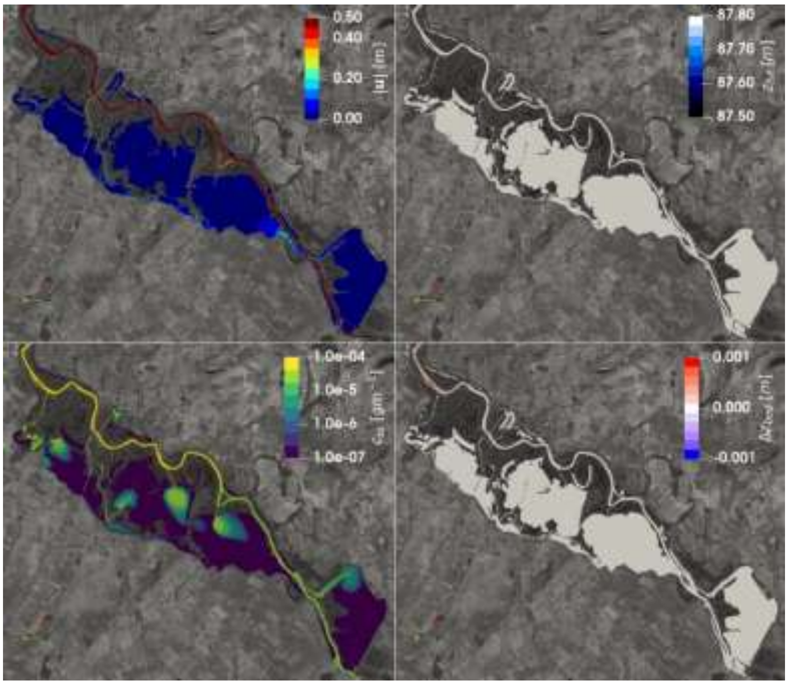

Figure 14 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 5.

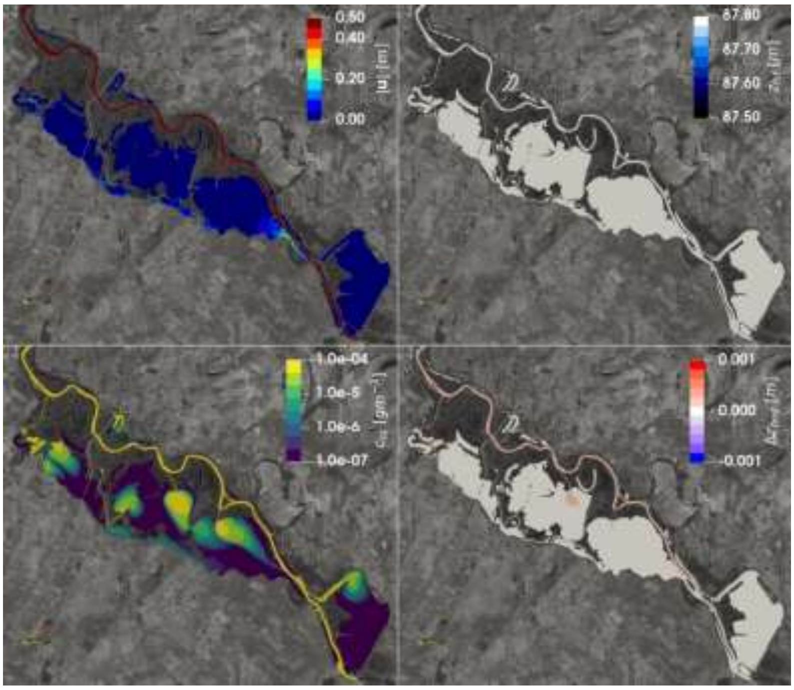

Figure 15 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 6.

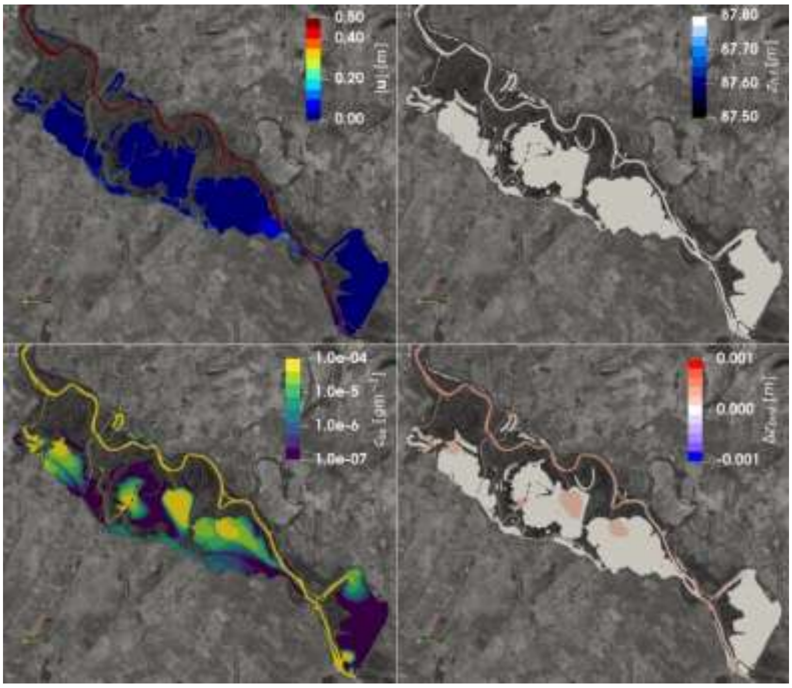

Figure 16 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 7.

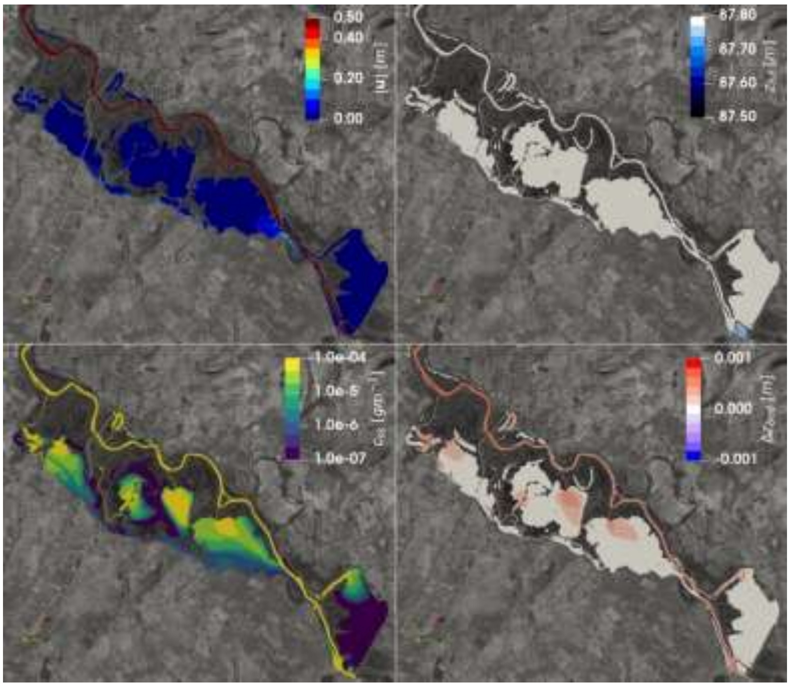

Figure 17 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 8.

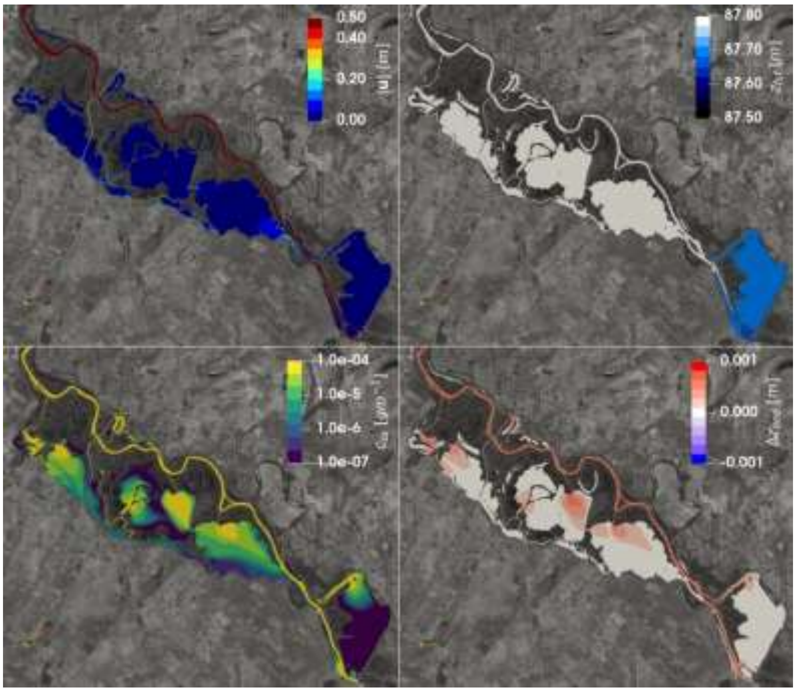

Figure 18 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 9.

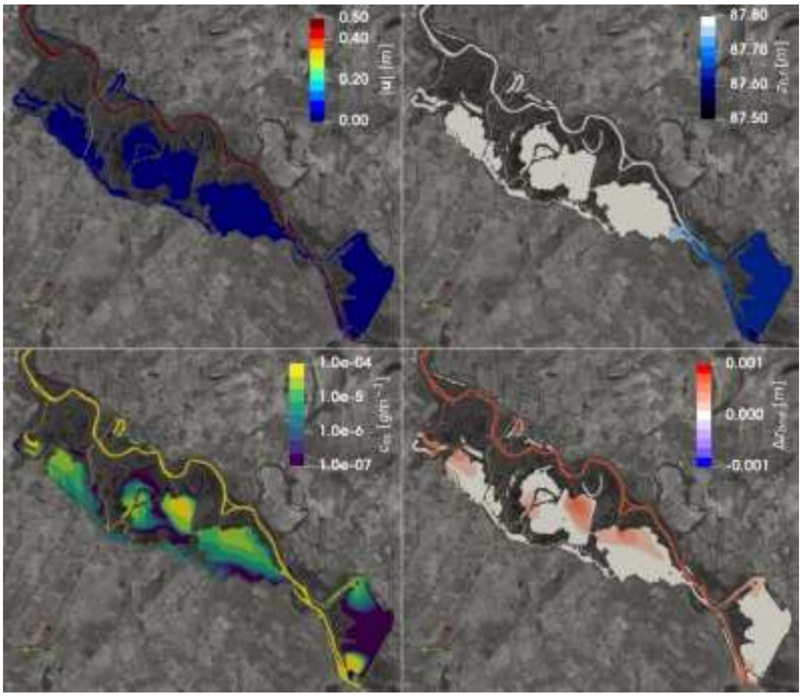

Figure 19 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 10.

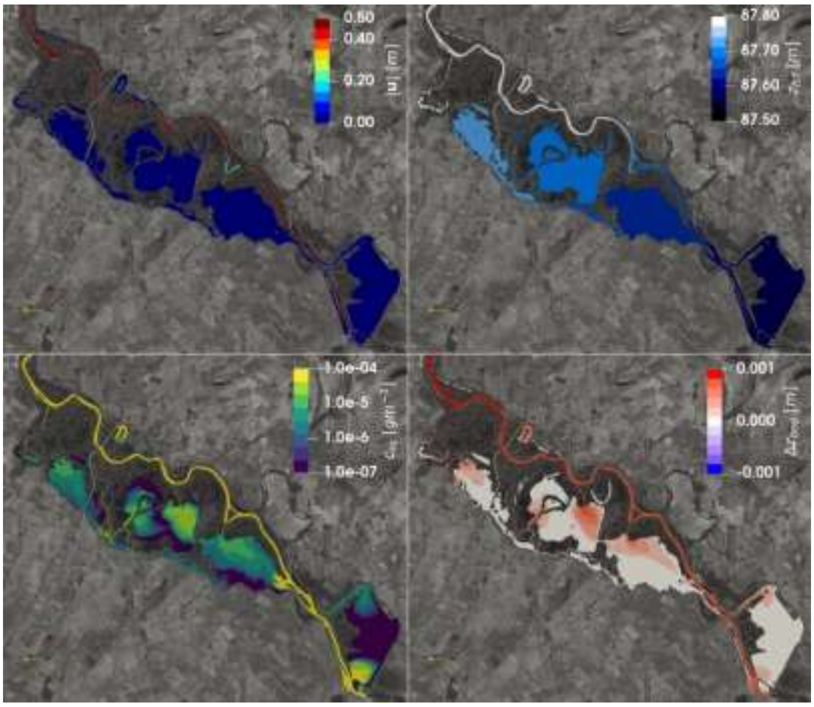

Figure 20 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 11.

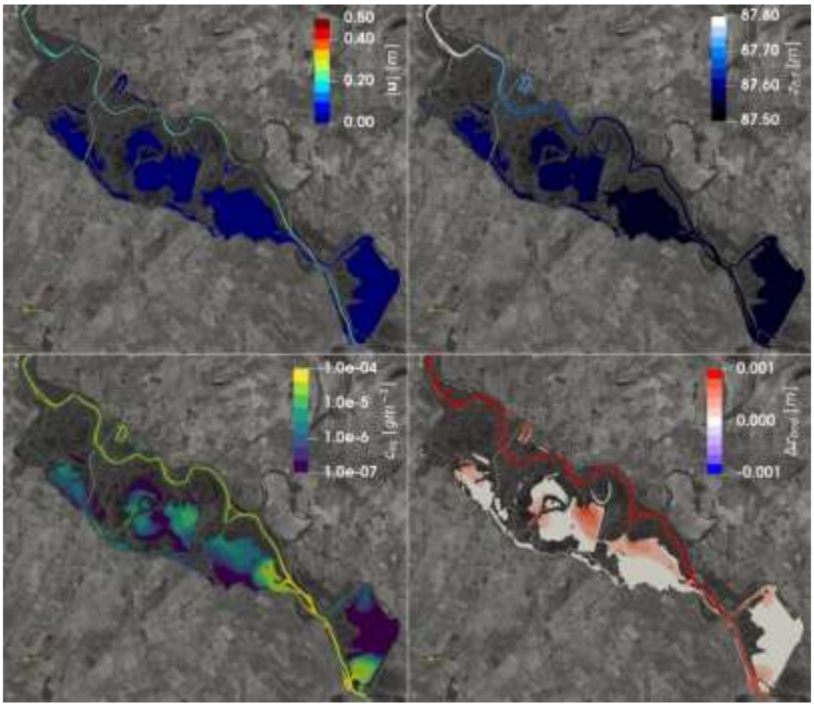

Figure 21 Spatial distribution of surface flow velocity magnitude (top left), water surface level (top right), suspended sediment concentration (bottom left) and bed elevation change (bottom right). Model scenario FW5, day 12.

Comparison of total sediment depositions

In case of reservoir operation, the most relevant aspect of suspended sediment transport is the fate of the fine particles, that is whether they are transported downstream, or settle within the basin(s). As a result of different reservoir operation scenarios, one can not only expect differences in the hydrodynamic conditions, but in the consequent bed morphology as well. The thickness of the deposited sediment layer for the different scenarios is presented below (**Figure 22**).

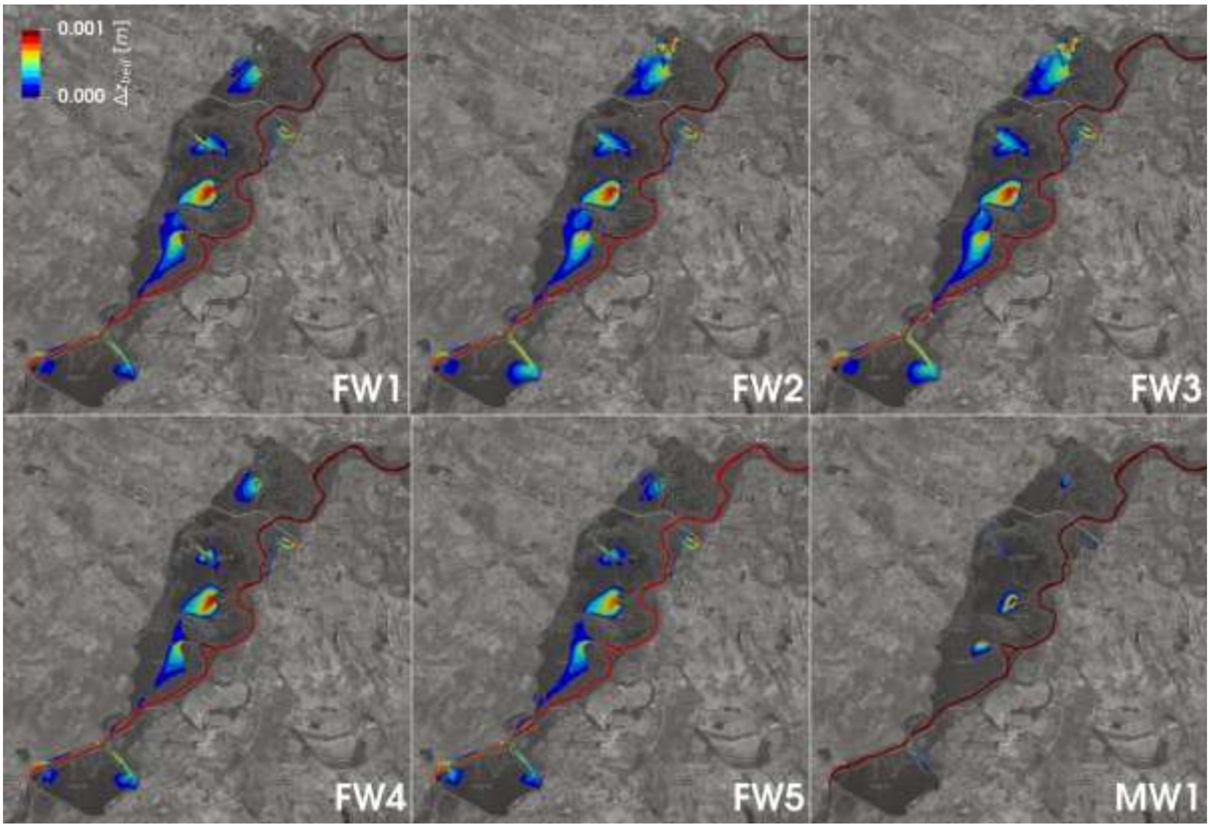

Figure 22 Final thickness of the deposited sediment layers at the end of the investigated model scenarios

The importance of reservoir morphology is emphasized – while notable differences are observed between the examined scenarios, the general patterns and the main hotspots of sediment deposition are different throughout the modeled cases. The main results of **Figure 22** are summarized in the following bullet points. Results are to be assessed in the light of the boundary conditions used in the various simulations (**Figure 5**).

- FW2 can be considered as a reference case, where the dam operation at Kisköre does not change during the simulation, that is the water level is kept constant throughout the whole flood wave. Almost the highest depositions are observed in this scenario, showing that proper dam operation may indeed play a crucial role.
- Dam operation in model variants FW1 and FW4 both aimed to prevent the settling of fines in the reservoir through the reduction of the water level at Kisköre

Dam. In case of the latter (FW4), the drawdown starts at the same time the flood wave, which – according to the model – results in slightly more efficient flushing.
- The highest amount of retained sediments is expected in FW3, where the water level is increased at the dam, resulting in lower velocities, turbulence and hence deposition rates. These hydrodynamic conditions make this model variant the most contra productive from the aspect of reservoir sediment management, which is well represented by the highest amount of deposited fines.
- The most intense drawdown (flushing) is performed in FW5, where the water level at the dam is increased prior to the flood wave, in order to facilitate a more intense flushing (drawdown of 1 m). The model results underline the efficiency of such an approach – the lowest level of deposition occurs from the flood wave scenarios.
- The long-term mean flow condition (MW1) entails marginal amount of sediment deposition in the reservoir.

On one hand, the predicted depositions are so small in the reservoir (~ 1 mm) that they almost seem negligible, but on the other hand it is emphasized, that reservoir management has to cover much longer time periods, where the cumulative effects of such small sedimentation events may result in notable losses in the long run.

Effect of erosion modeling

In the previously presented simulations, the model did not take account for the potential erosion of sediments, only the fate of suspended sediments was investigated. The role of erosion is also of great importance, especially when the effect of flushing is to be predicted. The effect of erosion modeling is assessed in the following brief example, where the FW5 model variant was recalculated in a way, that bed erosion was also allowed (FW5e). The comparison of the two model variants is presented in **Figure 23**.

Figure 23 Comparison of final bed level change without (left) and with (right) erosion modeling.

The locations of the major deposition patches mostly remain unchanged; however, the erodible bed model also highlights areas of potential erosion. The authors note that the proper parametrization of such an erodible bed model would require a large amount of field data (e.g., grain size distribution of the surface of the bed, as well as the layers below). Thus, the results presented here – while believed to be plausible – do not represent reality in the present form. Nevertheless, this additional numerical computational experiment highlighted the relevance of erodible bed modeling in reservoir modeling.

Summary and conclusions

As an introduction, the brief summary of the impacts of reservoir sedimentation was given based on actual scientific literature. The relevance and importance of reservoir flushing was underlined, while the potential problems and conflicts of interests were also highlighted. Three-dimensional CFD modeling is a potential tool for the impact analysis and planning of reservoir flushing, which was presented through a series of successful implementation found in the literature.

This study aimed to provide a brief summary on the potential of such 3D morphodynamic modeling, through the example of the Lake Tisza, which the largest reservoir of the Tisza River in Hungary and has become a major ecological treasure since its creation. After the short introduction of the reservoir, a short summary was given on the applied numerical model (SSIIM). The process of model building was briefly presented, to give a reader an overview on how raw data is transformed into a structured and functional base of hydrodynamic simulations.

The constructed numerical model was used to perform simulations with varying hydrological conditions and dam operations – the latter is considered to be the sediment management tool of highest potential. A short overview was given on the nature of the numerical results, to help the reader interpret the general ideas behind such model simulations. All together seven different model scenarios were simulated with the numerical tool. The efficiency of different dam operations was presented through the comparison of final sediment deposition maps. Based on the findings of this study, the following conclusions can be drawn:

- Three-dimensional CFD modeling is an adequate tool for the numerical approximation of the prevailing hydrodynamic conditions and as such, must be considered as a powerful tool in reservoir management.
- The coupling of the hydrodynamic model with a suspended sediment transport model can provide deep insights to the nature and behavior of complex morphodynamic systems, such as the Lake Tisza. Properly defined set of boundary conditions can be used to investigate different scenarios for the same hydrological event with varying dam operation. Via the post-processing of the model results, easily interpretable maps can be generated, which can not only help experts, but decision makers as well to improve reservoir management.

References

1. Dargahi B. (2012) *Reservoir Sedimentation*. In: Bengtsson L., Herschy R.W., Fairbridge R.W. (eds) Encyclopedia of Lakes and Reservoirs. Encyclopedia of Earth Sciences Series. Springer, Dordrecht.
2. Esmaeili T., Sumi T., Kantoush S.A., Kubota Y., Haun S. and Rüther N. (2017) *Three-Dimensional Numerical Study of Free-Flow Sediment Flushing to Increase the Flushing Efficiency: A Case-Study Reservoir in Japan*. Water 9:900, 22p.
3. Haun S., Kjærås H., Løvfall S., Olsen N.R.B. (2013) *Three-dimensional measurements and numerical modelling of suspended sediments in a hydropower reservoir*. Journal of Hydrology 479:180-188.
4. Haun S., Olsen N.R.B. (2012a) *Three-dimensional numerical modelling of reservoir flushing in a prototype scale*. International Journal of River Basin Management 10(4):341-349.
5. Haun S., Olsen N.R.B. (2012b) *Three-dimensional numerical modelling of the flushing process of the Kali Gandaki hydropower reservoir*. Lakes & Reservoirs: Research and Management 17:25-33.
6. Heidarzadeh N., Motiey Nejad O. (2017) *Evaluating sedimentation effect on reservoirs water quality: a case study, Shadriyar reservoir*. Int. J. Environ. Sci. Technol. 14:2623-2636.
7. Jowett I. (1984) *Sedimentation in New Zealand hydroelectric schemes*. Water Int. 9:172-176.
8. Mahmood K. (1987) *Reservoir Sedimentation: Impact, extent and Mitigation*. World Bank Technical Paper, World Bank, Washington, DC. 71; ISSN 0253-7494, ISBN 0-8213-0952-8.
9. Olsen N.R.B. (2018) *A Three-Dimensional Numerical Model for Simulation of Sediment Movements in Water Intakes with Multiblock Option – SSIIM User's Manual*. Department of Civil and Environmental Engineering, NTNU.